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Infrastructure for CCS in the Skagerrak/Kattegat region, Southern Scandinavia: A feasibility study

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Abstract

This paper gives an overview of results from a project which explored the feasibility of establishing a CO_2 Capture and Storage infrastructure in the Skagerrak/Kattegat region of Southern Scandinavia. This involves assessment of the technical and economic parameters of the complete CCS chain and, in particular, identification of possible storage locations.

The project ran from June 2009 to December 2011. Emissions from three major industrial clusters in the Skagerrak/Kattegat region – Gothenburg in Sweden, Grenland in Telemark County, southern Norway and Aalborg in Denmark - were targeted. Both emissions from process industries as well as power plants were included.

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Keywords: CCS infrastructure; Skagerrak; Kattegat; Gassum formation; CCS cost; process industrial CO_2 sources

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1. Project background and scope

Within the Skagerrak/Kattegat region, Southern Scandinavia (fig. 1), there are several industrial and energy-related clusters. Within a radius of approximately 100 km 14 $MtCO_2$ are emitted to the atmosphere from large point sources, each with an annual emission level of 0.3 $MtCO_2$ or greater. Industrial CO_2 sources contribute approximately 25% of the total Scandinavian (Norway, Denmark, Sweden) greenhouse gas emissions. The industrial sources cover several branches, from petrochemicals, fertilisers, refineries, and cement, to the pulp and paper industry. All of these industries are facing different situations regarding competition and business challenges [1].

In this study, post-combustion CO_2 capture technologies were assumed to be implemented using state-of-the-art MEA technologies for the industrial plants and in addition chilled ammonia technology for the power plants. This implies a demand for a low-quality steam supply to the stripping part of the capture plants.

The CO_2 capture potential is estimated to be in the range 6 to 14 million tonnes (Mt) of CO_2 annually when including sources > 0.3 Mt CO_2/y. The figures were estimated partly through site visits combined with rough assessments of technical feasibility of CO_2 capture and partly by using figures supplied by plant management. The higher figure includes all industrial and power-generating sources within the mentioned region. Therefore, a scenario for this level of CO_2 was chosen when developing transport and storage options.

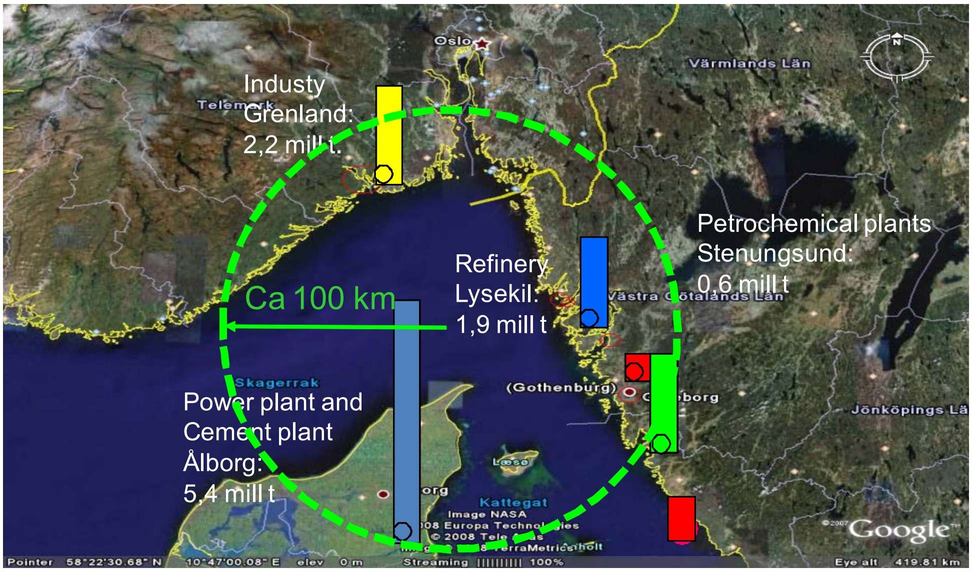

Fig. 1. The Skagerrak/Kattegat region showing the distribution of main CO_2 sources.

This project addressed the entire CO_2 value chain, including CO_2 capture at industrial sites, finding an optimal CO_2 transport infrastructure, and the use of available geological and seismic data to identify a possible storage site.

Furthermore, the regulatory framework that must be in place to implement CCS in this region was examined. As is typical for regional projects across national borders, several trans-boundary issues and legal matters need to be resolved. However, this part of the work is not dealt with in this paper. For information, please see [1].

2. CO_2 capture in the Skagerrak/Kattegat region

The CO_2 emissions in this region are related to both energy demand and specific industrial process sources.The study includes three refineries, two chemical plants, and two power plants (Table 1). In contrast to power plants, CO_2 emissions from industrial sources often originate from several sources within each facility, which of course complicates the process and increases the cost for capture. It is also important to note that the sources within a specific plant may differ in terms of the quantity and quality of the CO_2 and, thus, also in terms of capture cost. This work investigates each plant on an aggregated level. Table 1 lists the industries and power plants that are investigated along with their approximate annual CO_2 emissions and the number of relevant sources at each facility. The specific cost of CO_2 capture is likely to increase with lower total emissions and increasing number of emission sources.

Table 1. Plants analysed in the present project, showing their annual CO_2 emissions and the numbers of CO_2 sources at each facility

Industry	Country	Installation name	CO_2 emissions kt	No. of relevant CO_2 sources
Refinery	Sweden	Preemraff Lysekil	1,800	4
Refinery	Sweden	Preemraff Gothenburg	544	2
Refinery	Norway	Esso Slagentangen	365	9
Chemicals	Norway	Yara Porsgrunn	726	3
Chemicals	Sweden	Borealis Cracker	730	9
Power station	Denmark	Nordjyllandsverket	2,000	1
Power station	Sweden	Ryaverket	400	1

For all the examined plants apart from the power plants, amine based post-combustion capture has been the capture technology which has been considered in this project. This was to secure a common basis for cost estimation and also because all the plants in question are in operation. Another post-combustion technology, chilled ammonia, was examined for the power plants. In this paper, we have restricted the detailed description to cover process industrial plants, including one representative example (a refinery).

2.1Capture from process industrial sources in the region

To supply the necessary heat in the desorption reboiler, different options are proposed. One option is to use the excess heat in the existing process, possibly by using heat pumps to achieve the necessary temperature levels. Other options are to invest in an external unit (e.g., a boiler) that would produce the necessary steam and also co-generate electricity. The costs associated with these alternatives are identified for each industrial plant. The target is to capture 85% of the generated CO_2, including the CO_2 generated during the capture process.

2.2 Cost calculation principles

To evaluate the feasibility of CO_2 capture, the cost of installing capture units should be compared to the cost of emitting CO_2 (e.g., the expected EU-ETS price). The cost for capturing CO_2 can be defined in two ways: 1) the cost of CO_2 captured (€/tCO_2 captured); and 2) the cost of CO_2 avoided (€/tCO_2 avoided). The difference between the two costs is that the cost of CO_2 avoided has a constant production and includes the emissions and costs of the additional units required to capture the CO_2. In contrast, the cost of CO_2 captured includes the cost for the loss of production. For CO_2 capture from industrial sources, the cost of avoided CO_2 is applicable, as the product cannot be used to power the capture process and thus, additional units are needed. For CO_2 capture from existing power plants, the cost for CO_2 captured is applicable, as these plants exploit the existing production of heat and electricity rather than installing new units to cover the extra demand.

Thus, for industry, the cost of avoided CO_2 is calculated as the capital and operating costs for the heat supply plant and capture plant divided by the avoided amount of CO_2 emitted, which is calculated as the difference between the emissions from a plant without capture and one with capture (including the heat supply plant).

2.3 Example: Preem Refinery, Lysekil, Sweden

The Preem refinery in Lysekil, Sweden, is a complex refinery with a crude oil refining capacity of 11.4 Mt/yr. CO_2 emissions from the oil refining process originate from several sources. Four sources represent 97% of the total emissions, and the emissions from these during a typical year are listed in Table 2. It is assumed that it is realistic to capture CO_2 from these sources.

Table 2. CO_2 emission sources; Preem Lysekil. The four chimneys referring to individual flue gas outlets.

	Chimney 1	**Chimney 2**	**Chimney 3**	**Chimney 4**
Temperature	160˚C	180˚C	270°C	170°C
Flow	450,000 Nm^3/h	270,000 Nm^3/h	90,000 Nm^3/h	150,000 Nm^3/h
CO_2 concentration	6.7 vol-%	9.1 vol-%	14.0 vol-%	24.0 vol-%
CO_2 emissions	500 kt/yr	400 kt/yr	240 kt/yr	600 kt/yr

2.4 Costs for industrial plants and power plants

In summary, the lowest specific capture costs for process industrial plants are achieved when excess heat is utilized. Specific capture costs of 45 €/tCO_2 to 60 €/tCO_2 (including cost of compression up to 75 bar) can be achieved in such systems using excess heat alone or in combination with a heat pump. The specific avoidance costs are the same for these systems, since no fossil fuel is used. Higher specific costs are incurred if the heat from the heat pump is not sufficient to cover the heat demand of the capture plant so that supplementary heat *via* a heat supply plant is needed. The results of the economic analyses of the costs of CO_2 capture for the power plant Nordjyllandsverket are in agreement with the results for coal-fired power plants presented in a report by ZEP (2011) [2].

3. CO_2 storage in the Skagerrak/Kattegat region

The adjoining onshore areas of southern Norway and western Sweden consist of old crystalline basement rocks without storage potential. Therefore, the only place to look for storage is within the sediments located offshore. This study consisted of an initial screening of potential CO_2 plays based on published work, followed by new seismic mapping and the interpretation of available well-logs and cores, with the aims of selecting the optimal traps/structures for CO_2 storage, performing petrophysical analyses, and estimating reservoir properties. Finally, reservoir simulation was performed for a few selected sites.

To establish a CCS infrastructure in the Skagerrak/Kattegat region it is necessary to identify and characterise potential CO_2 storage sites within reasonable distances of the major sources of CO_2 so as to minimise transport costs. Although the geology of the North Sea has been explored extensively over the past 40 years of oil and gas exploration, the Skagerrak/Kattegat region has not been opened for such exploration, with the result that its geology and reservoir characteristics are far less known (see figure 2). Therefore the aim here was to study the Kattegat, Skagerrak, and Eastern North Sea as well as on-shore parts of Denmark, to identify and characterise potential subsurface reservoirs for storing CO_2.

The main criteria for selecting a site for geological storage of CO_2 according to IPCC [3] are: adequate CO_2 storage capacity and injectivity; safety and security of storage (i.e., minimisation of leakage); and minimal environmental impact. Typical rocks that form seals or cap rocks in the area of study are mudstones, shales or fine-grained chalks.

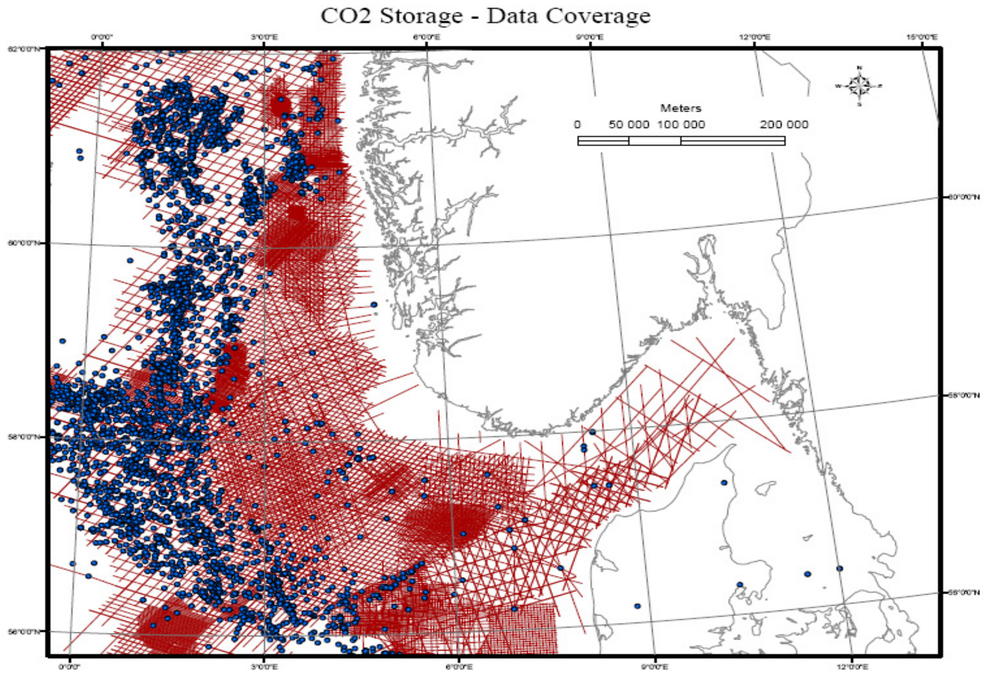

Figure 2.Overview map of the study area showing seismic dataset (lines) and the locations of wells (dots). From [4].

3.1 Selection and characterisation of geological sites

Possible storage plays in the Upper Paleozoic, Mesozoic, and Cenozoic sedimentary rocks were ranked. One formation, the Gassum Fm is overlaid by the thick mudstone sequences, providing an excellent seal and was chosen for this study. In addition, there is an upper seal toward the sea formed by the Quaternary mudstones. In general, thicker mudstone/shale formations make better seals, although even rather thin young sediments have been shown to be effective cap rocks. Generally, there is a 50 - 200 meter thick upper Quaternary seal in the area. The storage potential in Skagerrak is further elaborated in [5].

3.2 Reservoir simulations with CO_2 injection modelling

A reservoir simulation of CO_2 injection into the Gassum formation in the area north and north-east of the Fjerritslev Trough [6] was performed by SINTEF Petroleum Research [7]. Two open dipping aquifer models (Model 1, Model 2) with homogenous properties and homogenous thickness were made (Figure 3). In addition, a model of the Hanstholm structure just south of Model 1 was constructed in which initial simulations have been performed for estimating storage capacity. Details of the reservoir models, sensitivities and simulation results are given in a separate technical report. The locations of Model 1 and Model 2 were decided based on the concept of storing CO_2 in an open dipping trap. Thus, the injection points should be located down-flank of a gentle dipping formation. The main short-term mechanism for trapping CO_2 would then be capillary trapping the CO_2 as a residual phase. In addition, the long migration distance of the injected CO_2 would enhance the dissolution of CO_2 into the formation water. The Hanstholm structure, which is assumed to be a closed structure, was chosen for its size. The main short-term trapping mechanism in Hanstholm would be capillary trapping by the assumed sealing cap rock. Reservoir properties are based on the petrophysical logs from 12 Danish wells. In all three models, a total of 250 $MtCO_2$ is injected down-flank using three horizontal injection wells over a period of 25 years (base case). The total simulated time is 4000 years.

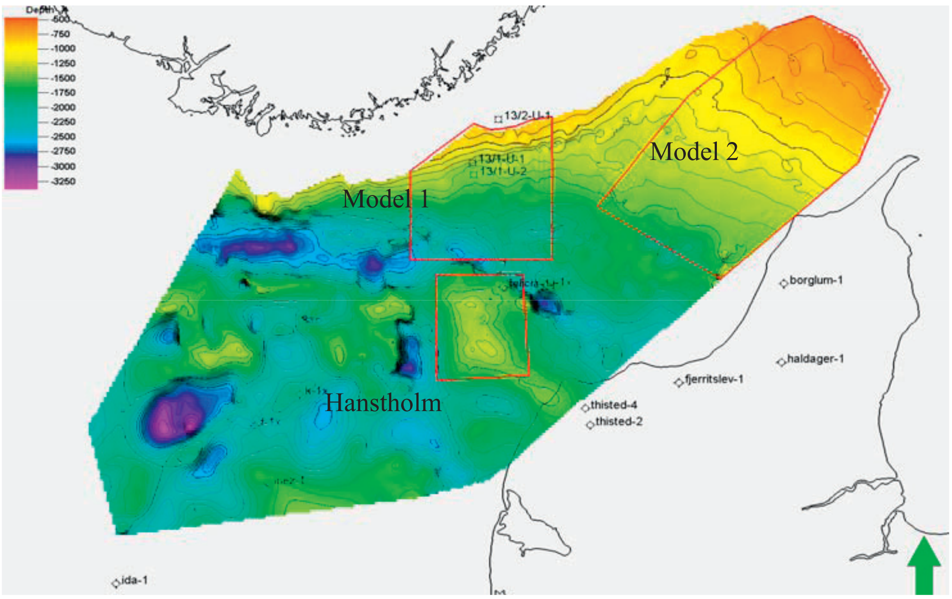

Figure 3. Outline of the areas for Model 1, Model 2 and Hanstholm shown on a top Gassum Fm. surface [5], [6], [7] .

For Model 1 the CO_2 reaches the northern border after 400 years, and after 4000 years 7.5% of the CO_2 has escaped. The remainder is capillary-trapped (~74.5%) or dissolved (~18%). For Model 2, even after 4000 years, all the CO_2 is retained within the model boundaries. Overall, ~24% of the CO_2 is dissolved after 4000 years, while the remainder is capillary-trapped (residual). Simulation of CO_2 injection into the Hanstholm structure has shown that the structure can accommodate 250 $MtCO_2$ injected down-flank using three horizontal injection wells over a period of 25 years. For the Hanstholm structure, injectivity properties and injection pressure may become a limiting factor with regard to storage capacity. In turn, this may generate a need for more injection wells and/or water producing wells.

The aquifer south of Kristiansand has been used as the basis for evaluations of the costs of CO_2 storage and transport. Storage costs, based on five injection wells and 14 Mt CO_2/y, are estimated at 9 €/tCO_2. The largest uncertainties lie in the drilling costs and the number of injection wells, so the estimate is considered an upper boundary.

4. CO_2 transportation

Transportation of CO_2 in the Skagerrak/Kattegat region has also been studied, from emission sources and to a point in the Skagerrak corresponding to a possible injection site. In addition, potential sources located not far from the core area could be linked to a future common CO_2 transport system. As transportation is the subject of another paper [8] only the main conclusions from the transportation study are referred to here.

CO_2 is delivered from the capture plant at 75 bar at a temperature of 20℃ and a water content of less than 500 ppm (vol%). Further conditioning depends on the type of transport. The cost element in regard to conditioning of the CO_2 beyond 75 bar and 20℃ is included in the transport cost. The mode of transport will govern the state of CO_2 during transport. For pipeline transport the CO_2 is kept at a pressure above 75 bar in order to ensure single dense phase. Ship transport takes place in liquid phase at 7 barg and -50℃.

The overall transport cost excluding compression is estimated to lie in the region of 12–14 €/tCO_2 when approximately 14 Mt of CO_2 are transported annually. The cost increases to 14–21 €/tCO_2 when approximately 6 Mt of CO_2 are transported annually. Under current assumptions, transportation of CO_2 by ship is the most cost-effective solution, although the costs differences among the various options lie well within the accuracy of the estimations. Other factors, such as limitations related to protected areas and quay access will therefore be of importance when planning the transportation infrastructure.

The estimated transport costs are comparable to those reported in similar studies. The Rotterdam Climate Initiative [9] calculated a cost of 25 €/tCO_2 for transport (including compression) and storage, while the Baltic Sea – project [10] estimated the cost to be 4–8 €/tCO_2 for transport (excluding compression) only.

A major challenge when evaluating the transport part of the CCS chain is the ramping up of CO_2 flows to the full capacity of the network. A sensitivity calculation shows that the transport cost would increase up to three-fold depending on the strategy chosen for handling the various load situations.

5. Next step

As a next step, the injectivity of the Gassum formation should be tested. Because of the relative similar lateral depositional system of the Gassum formation along strike, such testing could be performed at an onshore location, preferably in northern Denmark as close to the most likely CO_2 injection site as possible. Injection testing can be done in a new well by using water as a proxy for CO_2, thus avoiding the obvious challenges associated with CO_2 injection onshore. Core samples can be taken from the borehole and tested with regard to response to CO_2 in the laboratory.

An application to the Norwegian Climit programme has recently been submitted with regard to financial support for doing necessary preparations for such injectivity testing. Industry participation is secured for this part of the work.

Acknowledgements

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